CA1 HW1179 E33

CA1 HW 1179E33
Canada. DNHW. EHD.
79-EHD-33
LABORATORY TESTING OF POINT-OF-USE ULTRAVIOLET DRINKING
WATER PURIFIERS. 1979.

CA1 HW1179 E33

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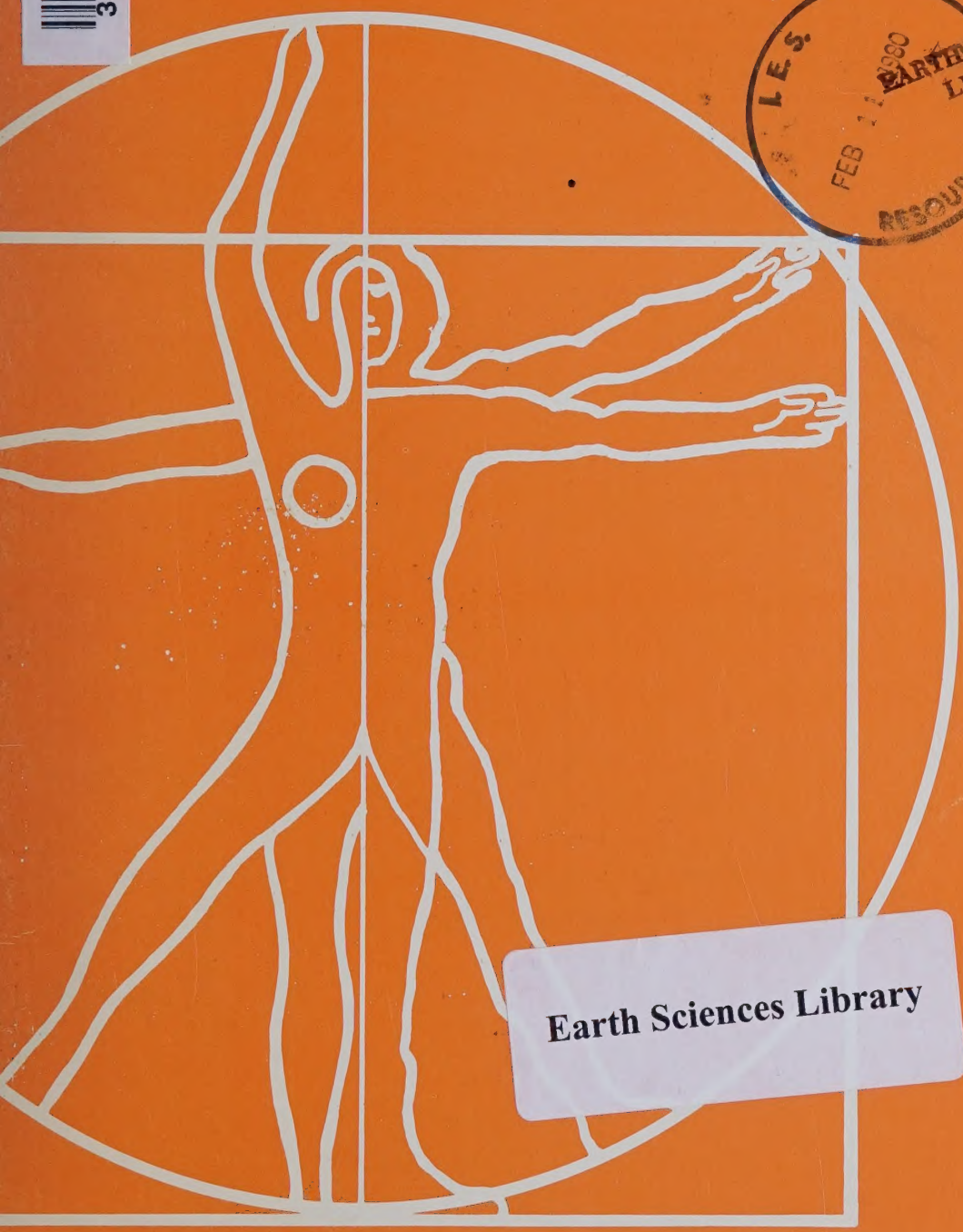

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LABORATORY TESTING OF POINT-OF-USE ULTRAVIOLET DRINKING WATER PURIFIERS

Environmental Health Directorate
Health Protection Branch

Published by Authority of the
Minister of National Health and Welfare

April 1979

79-EHD-33

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Information Services,
Department of National Health and Welfare,
Brooke Claxton Building,
Ottawa, K1A 0L2

ACKNOWLEDGEMENTS

This report was prepared by Dr. R.S. Tobin of the Bureau of Chemical Hazards and is based on work conducted under contract by Dearborn Environmental Consulting Services. Assistance provided by Dr. V.C. Armstrong of the Bureau of Chemical Hazards, who served as scientific authority for the study, and by Messrs. I. Marvan and R. Kissel of Dearborn Environmental Consulting Services during the preparation of this document is gratefully acknowledged.

SUMMARY

A test protocol for point-of-use water treatment devices utilizing ultraviolet (UV) light to destroy microorganisms has been developed. It was employed on three commercially available units, with different features, operating under conditions simulating the treatment of water polluted with bacteria. The devices were continuously challenged with Escherichia coli at a level of about 5000 cells/100 mL. Two of the units produced good water at both 4°C and 22°C and at design flow rates, one-half design flow rates, as well as rates greater than design flow rates. The other unit, which did not have a quartz sheath protecting the UV lamp from contact with the water, did not produce bacteria-free water at any of the flow rates in the 4°C water. At 4°C and the recommended flow rate, an average of 15.8 colonies/100 mL were found after treatment (range 6-26 colonies/100 mL).

These results point out the need for an accurately-calibrated UV light meter and alarm or fail-safe device incorporated into the device. Several recommendations are made with respect to the proper design and operation of UV water treatment devices.

RÉSUMÉ

Un protocole a été élaboré pour la mise à l'épreuve d'appareils servant à traiter l'eau, à l'aide de rayons ultraviolets, au point d'utilisation, afin de détruire les microorganismes qu'elle contient. Trois purificateurs vendus dans le commerce, présentant chacun des caractéristiques particulières, ont été mis à l'épreuve dans des conditions semblables à celles qui prévalent dans le traitement de l'eau contaminée par des bactéries. Des doses d'Escherichia coli (environ 5000 bactéries/100 mL) ont été utilisées. Deux des appareils se sont révélés efficaces à 4°C et à 22°C au débit moyen prévu par le constructeur, à la moitié de ce débit et à des débits supérieurs à celui qui avait été prévu. L'autre appareil, dont la lampe à rayons ultraviolets n'était pas protégée du contact avec l'eau par une gaine de quartz, n'a pas réussi à éliminer complètement les bactéries de l'eau à 4°C, quel que soit le débit. Au débit recommandé par le fabricant, l'eau traitée à 4°C contenait encore 15.8 colonies/100 mL (soit, de 6 à 26 colonies/100 mL).

A la lumière de ces résultats, on peut conclure que chaque appareil devrait comporter un dispositif de mesure de la lumière ultraviolette calibré avec soin, de même qu'un avertisseur ou un dispositif à sécurité intégrale. Plusieurs recommandations sont faites au sujet de la conception et des modes de fonctionnement des appareils de traitement de l'eau par les rayons ultraviolets.

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INTRODUCTION

Public awareness of potential water contaminants and a continuing interest in recreational activities in areas which may not be serviced with safe drinking water have led to increased usage of water treatment devices. The Bureau of Chemical Hazards of the Environmental Health Directorate has initiated studies to determine the efficacy of some of these devices and a survey of the various types available and possible testing procedures has already been published (1). Among these devices, the ultraviolet (UV) sterilizers are a possible choice where the presence of pathogenic bacteria or viruses is considered one of the major water problems.

UV treatment does not require any chemicals and does not affect the taste of the water; it works rapidly and the equipment requires little maintenance; changes in flow rates within the operating range of the unit present no problem; an overdose presents no danger and is considered a safety factor.

UV water sterilizers contain a low pressure mercury vapor lamp with about 85% of its light output near 253.7 nm(2). Water passing through the cylinder in which the lamp is situated is subjected to the ultraviolet light while passing through the system. The germicidal effect of the lamp is the result of action on the nucleic acids of the bacteria and is dependent upon the light intensity and exposure time by the following equation (3):

$$N = N_o \exp \frac{-Et}{Q}$$

where:

N is the number surviving,

N_o is the number before treatment,

E is the intensity,

t is the exposure time,

and Q is the unit lethal exposure.

To determine the effect of varying exposure times, the units were tested at different flow rates (i.e., exposure time): at the (manufacturer's) design flow rate, one-half the design flow rate and greater than design flow rate.

The light intensity can be affected by a number of factors which include:

- Temperature; the optimum operating temperature of the lamp is about 40°C. If the lamp becomes cooled by contact with the water, output may drop considerably.
- Line voltage; decrease in line voltage can cause a very significant decrease in lamp output.

- Ageing; newly installed UV light lamps have shown a decrease in radiation of approximately 20% during the first 100 hours of operation. There is only a minimal change over the next 7000 - 8000 hours of operation. At 7500 hours, the lamp output is still about 70% of that of a new lamp. Lamp manufacturers normally recommend the replacement of lamps after 7500 hours of service or every 10 to 12 months.
- Water composition; the presence of turbidity, colour, dissolved iron and organic compounds can affect the performance. The effectiveness of a UV device would be reduced due to clumping of organisms or shielding of organisms from radiation by particulate matter present, or by absorption of the UV light. Iron may be deposited on the emitting lamp or enclosing quartz glass tube which interferes with the penetration of the radiation into the water.

MATERIALS AND METHODS

UV Units Examined

Three commercially-available units, designed for point-of-use water treatment, were tested. The characteristics of the units are as follows:

Unit	Design Flow L/min	Meter	Lamp Watts	UV Exposure at Design Flow μwatt-sec/cm^2	Quartz Jacket[c]	Mechanical Cleaner[d]	Material[e]
A	30.1	Yes[a]	-	-	Yes	Yes	S. Steel
B	30.1	Yes[a]	40	35 000	Yes	No	S. Steel
C	7.6	No[b]	30	31 870	No	No	A.B.S.

a. Optional

b. A light-emitting diode signals that the lamp is drawing sufficient current to operate properly.

c. The presence or absence of a quartz jacket separating the UV lamp from the water.

d. The presence or absence of a mechanical scraper for cleaning the surface in contact with the water.

e. The material from which the outer jacket is constructed (stainless steel or A.B.S. plastic).

Challenge Bacterium

For purposes of this testing, Escherichia coli ATCC-25922 was chosen as the challenge bacterium. An examination of the American Type Culture Collection (ATCC) catalogue gave no indications that this strain would show any unusual resistance or sensitivity to UV irradiation. Also, the ATCC strain of E. coli was used in order to facilitate any future comparison studies.

Methods and materials for the total coliform membrance filter procedure were selected according to APHA Standard Methods, 14th Edition (5) with a few alterations to provide maximum recoveries. The choice of assay for the E. coli with a total coliform procedure instead of a fecal coliform procedure was made to enhance bacterial resuscitation rates (6, 7).

A sterilized solution of 0.1% peptone and 0.7% glutamate in double distilled water, with a final pH of 6.8 was substituted for buffered water used for washing and diluting the sample (1). The m-Endo LES agar medium (5) was prepared in sterile double deionized water (conductivity 2.6 micromhos/cm) according to the directions provided by Difco Laboratories, Detroit. The 47 mm gridded HC Type membrance filters (Millipore Corporation) were incubated on m-Endo LES agar in a 30°C incubator (Thelco, Precision Scientific, Chicago) for 24 ± 2 hours. Colonies with the characteristic coliform appearance as described in Standard Methods were counted.

Cultivation of the diluted E. coli culture was performed under uniform conditions of incubation. This was done to ensure that the bacteria were in essentially the same physiological state before being exposed to UV irradiation.

Figure 1 summarizes the procedure used to cultivate the bacteria for the dosage system connected to the test apparatus. All media used were the Bacto brand, supplied by Difco Laboratories, Detroit. Incubations were performed in Thelco incubators (Precision Scientific, Chicago). Any culture used in this cultivation scheme was propagated through three daily passages on TGE (Typtone Glucose Extract) agar slants at 35°C before use.

Parameters Measured

Factors affecting UV output include water temperature, line voltage, absorbance of the water, and flow rates. The UV light output of the lamp was measured as a function of these variables in order to make correlations with the degree of bacterial kill.

For each unit, three flow rates were evaluated in order to assess the safety factor and the effect of the design of the unit on flow patterns within the unit. These represented half the recommended flow rate, the recommended flow rate and a flow rate greater than the recommended value. The units were tested at two water temperatures, warm (22°C) and cold (approximately 4°C).

Line voltage was measured continuously during the test runs. Three samples were taken from the influent stream prior to the dosing of microorganisms for testing of absorbance at 253.7 nm.

The intensity of the UV light produced by the unit was continuously monitored during the test runs at a point approximating the farthest distance of the test water from the light source.

A summary of the testing program for each unit appears in Table 1.

Test Apparatus

The testing system used during the course of this project is shown in Figures 2 and 3. Figure 2 shows the set-up used for all runs except the low flow warm temperature water runs for the unit C which required a slightly modified system as shown in Figure 3. These modifications were necessary to maintain steady low flows.

For the warm water performance tests influent cold and warm water were mixed using an inline blender to deliver the warm temperature water. Cold water as supplied to the laboratory was used for the cold temperature water runs. The line pressure and flow were adequate for the testing so there was no need for inline pumping of the feed water.

The entire system was designed to accurately control and monitor the flow and water temperature. For the testing of unit C under the warm water, low flow rate conditions, this water supply system had to be modified (Figure 3). A continuously stirred 205 L tank and supply pump were substituted for the inline blender. Otherwise, the systems were identical.

The inflow stream, after adjustment to the required temperature, passed through a flow control valve where the desired flow was set. The inflow stream then passed through a carbon filter. A valve fitted in the line after the filter was used to sample for the presence of background bacteria and UV absorbance testing. An inline rotameter and thermometer were used to measure the flow through the system and control the temperature of the influent water. The rotameter was equipped with a direct reading scale for instantaneous flow determinations.

The prepared culture of E. coli was contained in a continuously stirred 1 litre glass bottle and was delivered to the dosing apparatus by a variable speed peristaltic pump. This eliminated any possible contamination of the culture by the pump. The variable speed motor allowed changes in the culture dosing rates. The dosing apparatus consisted of a 90-degree glass tube elbow which was inserted into the piping. The elbow helped ensure adequate mixing by causing some additional inline turbulence. Also no portion of the dosing culture could escape from the pipe should a minor leak in the hole occur.

An inline mixer was used after the dosing system to further promote mixing of the dosed culture with the rest of the water flow. A sampling port prior to the disinfection unit was used to sample the dosed stream to check its bacterial concentration.

The dosed influent stream then passed through the UV unit being tested. For units A and B the ultraviolet light intensity was monitored during the test runs on a continuous basis. An accurately calibrated UV meter which had three scale levels and a remote probe was used. The line voltage supplied to the unit was continuously monitored using an "Amprobe" line voltage meter which produced a graphical record of the voltage using an integrated strip chart recorder. For the test runs of the unit C, no UV light intensities were recorded during the testing of bactericidal effectiveness of the unit. The bactericidal testing was completed first, then the unit was modified to accept the UV light intensity sensor. The test runs were repeated and the UV light intensity was recorded. During this repeat testing of the modified unit, line voltage was again continuously monitored.

The treated water stream flowed through a short length of pipe from which the treated samples were gathered. The remainder of the flow was directed to the sewer for disposal.

PVC piping and fittings were used throughout the test system and all joints were teflon-taped to ensure that no leaks would occur during the testing.

Prior to the commencement of the test runs using an E. coli challenge, the system was tested using a solution of 29 000 mg/L orthophosphate instead of the bacterial culture. This was done to examine the dosing of bacterial challenge and mixing regime in the system. The concentration of phosphate in the water after dosing and running through the system varied by only ± 3% over a period of time equivalent to a test run. The results indicated that a dosed bacteria culture would be adequately mixed in the water stream entering the purifier.

During the testing, samples were collected in 250 mL clear glass bottles which contained sodium thiosulphate to provide a final concentration of 100 mg/L in the sample. This was added to remove any traces of disinfectant possibly present in the influent water.

Test Procedure

The bactericidal performance of each device was tested by dosing the influents to the units with Escherichia coli at levels of approximately 1000-5000 bacteria per 100 mL, as described previously (1); this level of challenge corresponds to the maximum total coliform level at which conventional treatment technology may be used in municipal water treatment plants (4).

Prior to the start of testing, the three test units were operated for 100 hours. This was done to allow the low pressure mercury lamps to age so that ultraviolet light intensities emitted would be representative of those during long-term operation of the units (1).

All the test runs were conducted using identical procedures. Before each test, the water stream was allowed to flow through the test apparatus with UV lamp off for 30 minutes to ensure that the water was at the correct flow and temperature, to check for any leaks in the system and to allow the test unit's lamp assembly to be thoroughly flushed.

A sample of the influent water after the carbon filter was analyzed, on each day of testing, for total available chlorine. In all cases the total available chlorine concentration was less than the detection limit of the test which was 0.1 mg/L.

Table 3 indicates the actual flow and temperatures at which each unit was tested. Due to the physical limitation of the units, it was impossible to test either Unit B or Unit C at flows of twice their recommended flow rates. They were tested at 37.9 L/min or 125% of their recommended flow rates.

Water was passed through the unit for a few minutes before the test to allow the temperature to reach equilibrium; time zero was defined as the moment the lamp was switched on. Three samples were taken (time zero, 7 minutes and 59 minutes) during the testing routine for the determination of the absorbance of the influent water. These samples were taken after the carbon filter but prior to the dosing of the bacterial culture.

Ultraviolet light intensity measurements were made throughout the test runs. Readings were recorded at 20 second intervals for the initial 5 minutes then at 5 minute intervals until the end of the test run. This procedure was used for units A and B only. An alternative method (as described in above) was used for the unit C.

The line voltage supplied to the test units was continuously monitored and a strip chart record was produced for each test run. During each test run one sample was taken from the influent stream after the carbon filter to determine whether there were any bacteria present in the stream prior to dosing. Also, three samples were taken of the influent stream after the dosing with the bacterial culture. These were taken at time zero, 7 minutes and 59 minutes during each test run to monitor the bacterial culture concentration prior to the UV treatment of the influent stream.

For each set of test conditions, a sampling regime extending over 59 minutes was adopted in order to assess the disinfecting ability of the test units. Samples of the treated stream were taken after the disinfection device at the start of testing followed by samples at 20 second intervals for 2 minutes, then at 5-minute intervals for the duration of the test.

The flow and temperature of the influent stream were constantly monitored by the technician operating the system. The feed system for the bacterial culture was also inspected frequently during the test runs.

RESULTS

Culture

When E. coli ATTC-25922 was cultured in the manner illustrated in Figure 1, the cell counts at 18 hours were in the order of 5×10^8 cells per mL. Based on this, dilutions were made in phosphate-buffered water (5) to serve as a stock for dosing the challenge water. Table 2 illustrates that this buffer has no inhibiting effect on the culture during a two-hour period in one experiment, and during a four-hour period in another experiment.

Water used in the test of UV units was chlorinated municipal tapwater which was dechlorinated just before use by passing it through a granulated activated charcoal filter. Residual chlorine measurements performed every day were below the detection limit of 0.1 mg/L total available chlorine. When a fifty-times dilution of the E. coli culture was made in this dechlorinated water (Table 2), no decrease in bacterial viability was observed.

UV Output

The absorbance of the water at 253.7 nm was measured at the beginning, at 7 minutes and 59 minutes of each test. The values ranged from 0.048 to 0.104 (Table 4) with an average of 0.095. These results indicate the presence of rather low levels of turbidity and organic material in the influent water and suggest that these tests were conducted under ideal water conditions for the UV devices.

The results of the measurement of UV intensity at 253.7 nm at a point farthest from the UV lamp are presented in Figures 4-9. Unit A consistently produced the highest UV intensity (about 10 000 $\mu watt/cm^2$) after a warm-up period of about 1 minute in 22°C water or 2 minutes in 4.4°C water. After this initial warm-up period, the lamp was quite stable for the duration of the test. There was little variation in output among runs at various temperatures and flow rates.

Unit B had an intermediate UV light which was about 4000 $\mu watt/cm^2$ in both warm or cold water. A warm-up period of about 1 minute in 22°C water and 2 minutes in 4.4°C water was required before the maximum UV light output was obtained.

Unit C apparently required no warm-up period in warm or cold water. The light emitted was constant with time in any given run, but the light output was very temperature dependent. It varied between about 6000 $\mu watt/cm^2$ in 22°C water to 1500 $\mu watt/cm^2$ in 4.4°C water. There was no significant association between light output and flow rate in this study.

As the UV output of lamps is voltage-dependent the line voltage operating the units was continuously monitored. A typical recording is shown in Figure 10. In no case was there a significant change in the voltage supplied to the units during the test runs.

Bactericidal Performance

Six different experiments were performed on each of the units. They consisted of low and high temperature water flows at low, design, and high flow rates. The influent total coliform levels measured at 0, 7 and 59 minutes (Tables 5-22) gave quite close agreement, verifying the constant flow and dosage rates. The bactericidal performance of each of the units is described separately below.

(a) Unit A

This device reduced the E. coli challenge to a level of less than 2 per 100 mL under all conditions (Tables 5-10) within 20 seconds of lamp start-up, with one exception. In this case (Table 7), a count of 4 colonies/100 mL was obtained at 40 seconds into the test. After this, no further coliforms were found.

(b) Unit B

This device consistently eliminated the bacterial challenge to a level below 1 colony/100 mL regardless of the flow rates in the 4.4°C water experiments after a 20 s warm-up period (Tables 11-13).

During tests with warm water, however, some positive samples were obtained on a few occasions. These were limited to low counts in three samples in high water flows (125 percent of design flow rate) (Table 14) and a single event of 6 colonies/100 mL in the effluent in the design flow rate (Table 15). This unit, after a 20 s warm-up period, reduced the bacteria in the effluent to less than 1 organism/100 mL in the low flow, 22°C water test (Table 16).

(c) Unit C

This device reduced the bacteria to less than 2 colonies/100 mL in warm water at all flow rates (Tables 20-22), with the exception of a single sample at the design flow rate (Table 21) where 58 colonies/100 mL were determined. An initial 2-minute period was required (Table 22) to attain this level of bacterial reduction.

Likewise, this device was capable of producing coliform-free water at 4.1°C and low flow rates (Table 19). It was, however, unable to effect sufficient bacterial reduction in 4.1°C water at the design, or greater, flow rates (Tables 17, 18). The experiments show that an average of 16 colonies/100 mL (range of 6-36) was obtained at the design flow rate and an average of 76 colonies/100 mL at the high flow rate (200 percent of the design flow rate).

DISCUSSION

Although it is clearly established that UV light can inactivate bacteria (3, 8-10), viruses (2, 11) and protozoans (12) when given in sufficient dosage, it is apparent from the results presented here that adequate testing of each commercially available UV model is required before it can be assumed that it will be capable of producing microbiologically safe water under various use conditions.

Two of the units tested here produced good, potable water from artificially contaminated dechlorinated tap water when operated at or below their design flow rate and allowing a two-minute warm-up period. Unit C, however, did not perform adequately, even at design flow rate, at low water temperatures which occur during cold seasons in many areas of Canada. Because the lamp is not jacketed with a quartz tube like the others tested, the bulb temperature is, to a large extent, dependent upon the water temperature; the light output decreased dramatically in cold water. Cortelyou et al. (8) demonstrated that the lamp output decreased about 80 percent when the water was cooled from 18.5°C to 4°C. In the present study, there was a decrease of about 75% in light output from 22°C to 4.1°C in unit C, where the water is in direct contact with the lamp. The UV dosage in the cold water with this unit was 13 500, 6750, 3375 μwatt-s/cm^2 at low, design, and high-flow rates respectively. The effect that UV dosage has on bacterial recoveries is illustrated in Figure 11. At the low-flow rate, all E. coli were inactivated after 2 minutes of warm-up. Faster flows (i.e., lower UV dosage) increased bacterial survival. When the UV dose is plotted against percent kill (Figure 12), it is found that complete E. coli kill (<1 colony detectable/100 mL) is obtained at a UV dose of 7080 μwatt-s/cm^2. This compares well with published dosages of 6470 to 6875 μwatt-s/cm^2 (2) for complete kill of E. coli. E. coli were used as a bacterial challenge because of their widespread use as a fecal indicator bacteria and because they are more resistant to UV light than most tested pathogenic waterborne bacteria and viruses (2, 12) although they are probably less resistant than some bacterial spores and protozoan cysts which may have to be removed by appropriate filters (12). The challenge level of 1000-5000 organisms/100 mL (1) was chosen because it corresponds to the highest level of total coliforms which is recommended for conventional complete treatment in municipal supplies.

Two of the units (A and B) had provision for a UV light detector to be mounted on a plane approximately the farthest distance in the unit from the UV lamp. Equipped with the proper meter, this allowed the continuous monitoring of UV intensity which could vary according to lamp aging, voltage changes, turbidity or colour of the water, iron deposits on the inside sleeves or other factors. By accurate measurement of the UV output at 253.7 nm and choosing an established UV dosage, the appropriate retention time (and thus flow rate) of a given device can be determined. A UV dosage of 16 000 μwatt-s/cm^2 was recommended

by the U.S. National Health, Education and Welfare Department (cited in 1) as the minimum acceptable level, measured at the point farthest from the light source. Even if devices are constructed and run to these specifications, it is clear from these studies that actual experiments are required to demonstrate that they work in practice. Further, since one may only rarely check a meter to ascertain that the UV output is in a satisfactory range, the provision of an audible alarm and/or a fail-safe valve is considered necessary. One should bear in mind, however, that if a normally energized solenoid is used, it could shut off due to power cut-off during emergencies, such as fires, when water is urgently required. On the other hand, if the solenoid is not normally energized, one has no way of knowing whether the system is still functional or not. In any case, an appropriate safety device can be designed that will minimize the possibility of unknowingly drinking inadequately-treated water and which will not cause any other major problems to the householder.

Further studies are currently underway to develop test methods to determine the efficacy of individual fail-safe devices on UV point-of-use water treatment devices.

RECOMMENDATIONS

1. All UV water treatment units should be provided with an accurately-calibrated light sensor that responds to UV light of 253.7 nm wavelength and that is coupled to a fail-safe device to prevent water flow or cause an audible alarm to be set off when the water is receiving a dose below 16 000 μwatt-s/cm^2. A water flow restrictor should be used to ensure the rated flow capacity of the unit is not exceeded.

2. All UV water treatment devices treating contaminated water should be installed with a filter capable of removing cysts greater than 5 μm in diameter.

3. A "systems approach" should be used to the installation of water treatment devices; factors such as iron content, turbidity and colour should be considered in the need for and selection of the auxiliary equipment to be used.

4. UV water treatment devices should not be used on raw water which is so polluted so as to require extraordinary means to purify it. An upper limit of 1000 total coliforms/100 mL or 100 fecal coliforms/100 mL is suggested for treatment by UV light. Advice on the suitability of using UV systems for treating a proposed source of drinking water should be sought from the appropriate health authorities.

5. All models of UV water treatment devices offered for sale in Canada for the treatment of microbiologically-contaminated water should be tested in tests similar to those described here to ensure that they adequately disinfect water. The turbidity and colour should be increased in the water to the point where the fail-safe device becomes operational, and at this point, the system must still maintain adequate disinfection.

6. UV light has no residual disinfection power and water may thus become recontaminated or regrowth of bacteria may occur. When drawing water after periods of non-use, including overnight standing, water should be allowed to flow for a sufficient time before using to ensure that freshly-treated water from the unit is obtained.

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TABLE 1

Testing Program for Each Unit

Flow Rate	Influent Water Temperature	Sampling Time																	Type of Sample	Number of Samples
		Seconds							Minutes											
		0	20	40	60	80	100	120	7	12	19	24	29	34	39	44	49	54	59	
Half Recommended Flow	Warm	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	E. coli
		1							1										1	Feed Stream
		1							1										1	Absorbance
	Cold	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	E. coli
		1							1										1	Feed stream
		1							1										1	Absorbance
Recommended Flow	Warm	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	E. coli
		1							1										1	Feed stream
		1							1										1	Absorbance
	Cold	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	E. coli
		1							1										1	Feed stream
		1							1										1	Absorbance
Greater Than Recommended Flow	Warm	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	E. coli
		1							1										1	Feed stream
		1							1										1	Absorbance
	Cold	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	E. coli
		1							1										1	Feed stream
		1							1										1	Absorbance
TOTAL PER UNIT																				E. coli
																				Feed stream
																				Absorbance

Number of Samples
18
3
3
18
3
3
18
3
3
18
3
3
18
3
3
18
3
3
108
18
18

TABLE 2

Total Coliform Counts in Samples of E. Coli Suspensions in Phosphate Buffer and Carbon Filtered Tap Water[(a)]

	Time			
	0 hour	1 hour	2 hours	4 hours
Experiment I				
Phosphate buffer	9×10^6	-	1.5×10^7	-
Experiment II				
Phosphate buffer	1.4×10^7	1.2×10^7	-	2.2×10^7
Carbon filtered tap water	1.4×10^7	-	-	2.4×10^7

a. One mL of an 18 hour nutrient broth culture of E. coli was added to 50 mL of diluent. The incubations were performed at room temperature (21 - 23°C) and the suspensions were stirred by a magnetic stirring bar throughout the incubation period.

TABLE 3

Flow Rates and Temperatures for Test Runs

Unit	Water Temperature (°C)		Flow Rates (L/min)		
	Warm	Cold	Half of Recommended Flow	Recommended Flow	Greater than Recommended Flow
A	22	4.4	15.1	30.3	37.9
B	22	4.4	15.1	30.3	37.9
C	22	4.1	3.8	7.6	15.1

TABLE 4

UV Absorbance of Feed Water Supply

Unit	Temp. °C	Flow L/min.	Time min.	A 253.7 nm	Unit	Temp. °C	Flow L/min.	Time min.	A 253.7 nm
Blank				0.000					
A	4.4	37.9	0	0.088	B	22	37.9	0	0.081
			7	0.080				7	0.084
			59	0.081				59	0.085
		30.3	0	0.071			30.3	0	0.082
			7	0.056				7	0.081
			59	0.061				59	0.083
		15.1	0	0.085			15.1	0	0.063
			7	0.065				7	0.058
			59	0.076				59	0.066
	22	37.9	0	0.075	C	4.1	15.1	0	0.067
			7	0.073				7	0.075
			59	0.078				59	0.075
		30.3	0	0.098			7.6	0	0.075
			7	0.076				7	0.058
			59	0.078				59	0.064
		15.1	0	0.054			3.8	0	0.047
			7	0.064				7	0.048
			59	0.060				59	0.050
B	4.4	37.9	0	0.088		22	15.1	0	0.104
			7	0.083				7	0.092
			59	0.082				59	0.051
		30.3	0	0.084			7.6	0	0.073
			7	0.084				7	0.067
			59	0.080				59	0.077
		15.1	0	0.081			3.8	0	0.104
			7	0.067				7	0.072
			59	0.068				59	0.051

TABLE 5

Disinfection of challenge water by Unit A
at high flow rate and high temperature.

Water Temperature: 4.4°C

Flow Rate: 37.9 L/min

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 9.0×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	5600	4600
20		<2
40		<2
60		<2
80		<2
100		<2
120		<2
7 Minutes	4600	<2
12		<2
19		<2
24		<2
29		<2
34		<2
39		<2
44		<2
49		<2
54		<2
59	5300	<2

TABLE 6

Disinfection of challenge water by Unit A
at design flow rate and low temperature.

Water Temperature: 4.4°C

Flow Rate: 30.3 L/min

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 12×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	300	1100
20		< 2
40		< 2
60		< 2
80		< 2
100		< 2
120		< 2
7 Minutes	600	< 2
12		< 2
19		< 2
24		< 2
29		< 2
34		< 2
39		< 2
44		< 2
49		< 2
54		< 2
59	1300	< 2

TABLE 7

Disinfection of challenge water by Unit A
at low flow rate and low temperature.

Water Temperature: 4.4°C

Flow Rate: 15.1 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 2.8×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	4100	4500
20		< 2
40		< 4
60		< 2
80		< 2
100		< 2
120		< 2
7 Minutes	4600	< 2
12		< 2
19		< 2
24		< 2
29		< 2
34		< 2
39		< 2
44		< 2
49		< 2
54		< 2
59	3800	< 2

TABLE 8

Disinfection of challenge water by Unit A
at high flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 37.9 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 1.1×10^8 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	5600	4400
20		<2
40		<2
60		<2
80		<2
100		<2
120		<2
7 Minutes	5200	<2
12		<2
19		<2
24		<2
29		<2
34		<2
39		<2
44		<2
49		<2
54		<2
59	4100	<2

TABLE 9

Disinfection of challenge water by Unit A
at design flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 30.3 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 5.3×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	2100	3600
20		< 2
40		< 2
60		< 2
80		< 2
100		< 2
120		< 2
7 Minutes	4300	< 2
12		< 2
19		< 2
24		< 2
29		< 2
34		< 2
39		< 2
44		< 2
49		< 2
54		< 2
59	3700	< 2

TABLE 10

Disinfection of challenge water by Unit A
at low flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 15.1 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 1.6×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	5300	3600
20		< 2
40		< 2
60		< 2
80		< 2
100		< 2
120		< 2
7 Minutes	5600	< 2
12		< 2
19		< 2
24		< 2
29		< 2
34		< 2
39		< 2
44		< 2
49		< 2
54		< 2
59	6700	< 2

TABLE 11

Disinfection of challenge water by Unit B
at high flow rate and low temperature.

Water Temperature: 4.4°C

Flow Rate: 37.9 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 1.1×10^8 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	8500	3100
20		< 2
40		< 2
60		< 2
80		< 2
100		< 2
120		< 2
7 Minutes	3600	< 2
12		< 2
19		< 2
24		< 2
29		< 2
34		< 2
39		< 2
44		< 2
49		< 2
54		< 2
59	20 000	< 2

TABLE 12

Disinfection of challenge water by Unit B
at design flow rate and low temperature.

Water Temperature: 4.4°C

Flow Rate: 30.3 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 4.9×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	4900	3500
20		<2
40		<2
60		<2
80		<2
100		<2
120		<2
7 Minutes	4500	<2
12		<2
19		<2
24		<2
29		<2
34		<2
39		<2
44		<2
49		<2
54		<2
59	3700	<2

TABLE 13

Disinfection of challenge water by Unit B
at low flow rate and low temperature.

Water Temperature: 4.4°C

Flow Rate: 15.1 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 2.6×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	4300	4400
20		<2
40		<2
60		<2
80		<2
100		<2
120		<2
7 Minutes	3000	<2
12		<2
19		<2
24		<2
29		<2
34		<2
39		<2
44		<2
49		<2
54		<2
59	4600	<2

TABLE 14

Disinfection of challenge water by Unit B
at high flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 37.9 L/min.

Background (Total coliform count): <1 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 1.1×10^8 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	6400	6700
20		< 1
40		< 1
60		1
80		< 1
100		< 1
120		< 1
7 Minutes	8400	< 1
12		< 1
19		< 1
24		< 1
29		25
34		3
39		< 1
44		< 1
49		< 1
54		< 1
59	5000	< 1

TABLE 15

Disinfection of challenge water by Unit B
at design flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 30.3 L/min.

Background (Total coliform count): <1 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 6.7×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	3400	4400
20		<1
40		<1
60		<1
80		<1
100		<1
120		<1
7 Minutes	3500	<1
12		<1
19		<1
24		<1
29		6
34		<1
39		<1
44		<1
49		<1
54		<1
59	3300	<1

TABLE 16

Disinfection of challenge water by Unit B
at low flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 15.1 L/min.

Background (Total coliform count): <1 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 6.7×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	10 000	8900
20		<1
40		<1
60		<1
80		<1
100		<1
120		<1
7 Minutes	7600	<1
12		<1
19		<1
24		<1
29		<1
34		<1
39		<1
44		<1
49		<1
54		<1
59	10 600	<1

TABLE 17

Disinfection of challenge water by Unit C
at high flow rate and low temperature.

Water Temperature: 4.1°C

Flow Rate: 15.1 L/min.

Background (Total coliform count): <1 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 6.0×10^6 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	1400	2200
20		58
40		61
60		96
80		65
100		73
120		74
7 Minutes	2300	65
12		64
19		85
24		82
29		96
34		67
39		83
44		97
49		78
54		74
59	1500	81

TABLE 18

Disinfection of challenge water by Unit C
at design flow rate and low temperature.

Water Temperature: 4.1°C

Flow Rate: 7.6 L/min.

Background (Total coliform count): <1 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 1.3×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	5500	5300
20		36
40		12
60		6
80		11
100		11
120		16
7 Minutes	5300	9
12		21
19		8
24		25
29		18
34		10
39		10
44		25
49		26
54		17
59	4700	8

TABLE 19

Disinfection of challenge water by Unit C
at low flow rate and low temperature.

Water Temperature: 4.1°C

Flow Rate: 3.8 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 2.3×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	6900	5500
20		70
40		22
60		6
80		6
100		2
120		< 2
7 Minutes	6000	< 2
12		< 2
19		< 2
24		< 2
29		< 2
34		< 2
39		< 2
44		< 2
49		< 2
54		< 2
59	5800	< 2

TABLE 20

Disinfection of challenge water by Unit C
at high flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 15.1 L/min.

Background (Total coliform count): <1 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 5×10^6 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	2100	3000
20		<1
40		<1
60		<1
80		<1
100		<1
120		<1
7 Minutes	2500	<1
12		<1
19		<1
24		<1
29		<1
34		<1
39		<1
44		<1
49		<1
54		<1
59	1600	<1

TABLE 21

Disinfection of challenge water by Unit C
at design flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 7.6 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 9.0×10^6 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	3500	5900
20		4
40		<2
60		<2
80		<2
100		<2
120		<2
7 Minutes	3300	<2
12		<2
19		<2
24		<2
29		<2
34		58
39		<2
44		<2
49		<2
54		<2
59	3300	<2

TABLE 22

Disinfection of challenge water by Unit C
at low flow rate and high temperature.

Water Temperature: 22°C

Flow Rate: 3.8 L/min.

Background (Total coliform count): <2 per 100 mL

Culture Feed Concentration Before
Culture Delivery Pump (Total coliform count): 1.4×10^7 per 100 mL

Elapsed Time	Total Coliform Counts per 100 mL	
	Influent	Effluent
0 Second	5400	10 000
20		32
40		14
60		8
80		4
100		2
120		<2
7 Minutes	7000	<2
12		<2
19		<2
24		<2
29		<2
34		<2
39		<2
44		<2
49		<2
54		<2
59	5500	<2

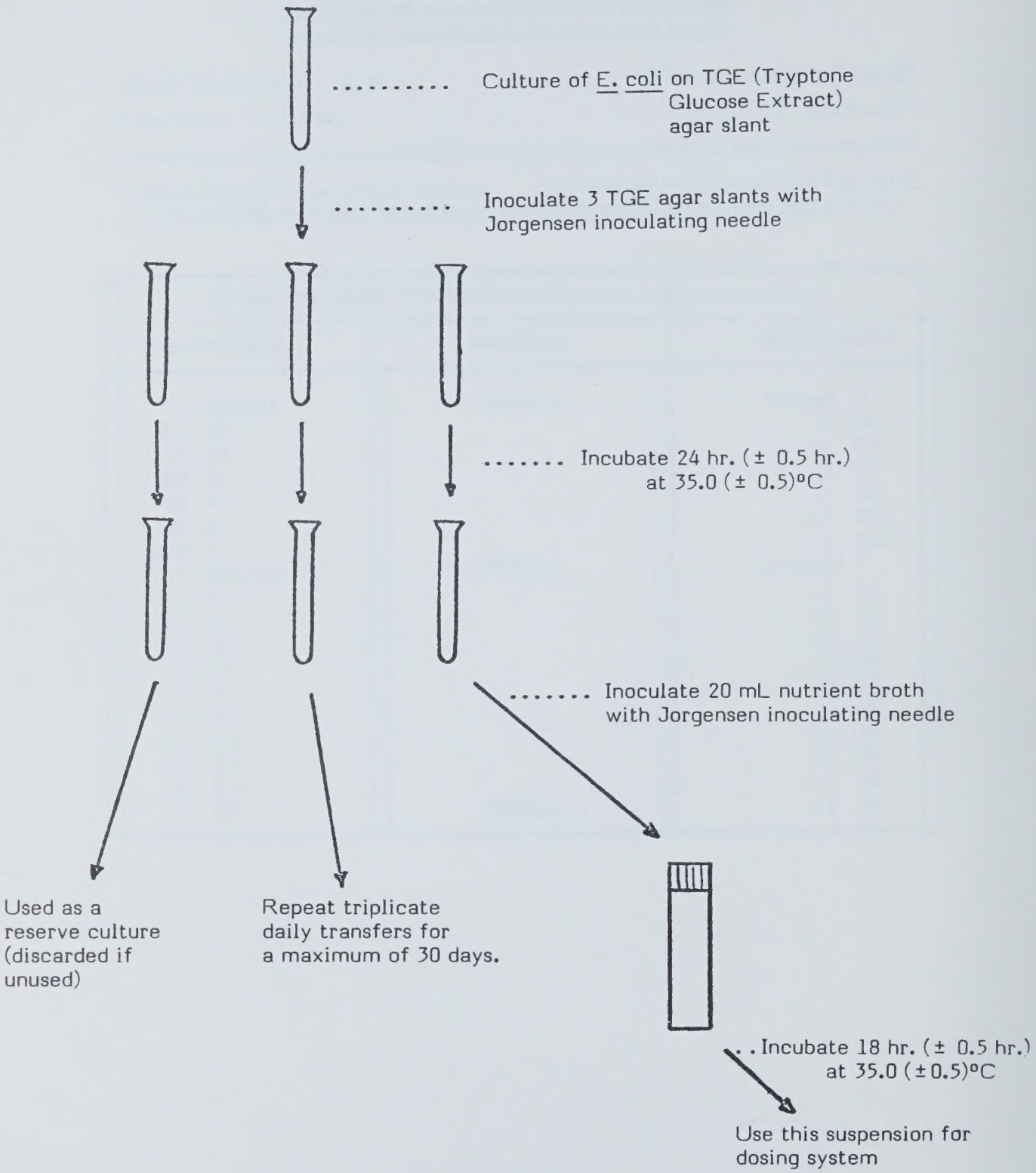

Figure 1. Procedure Used for Maintaining E. coli Cultures

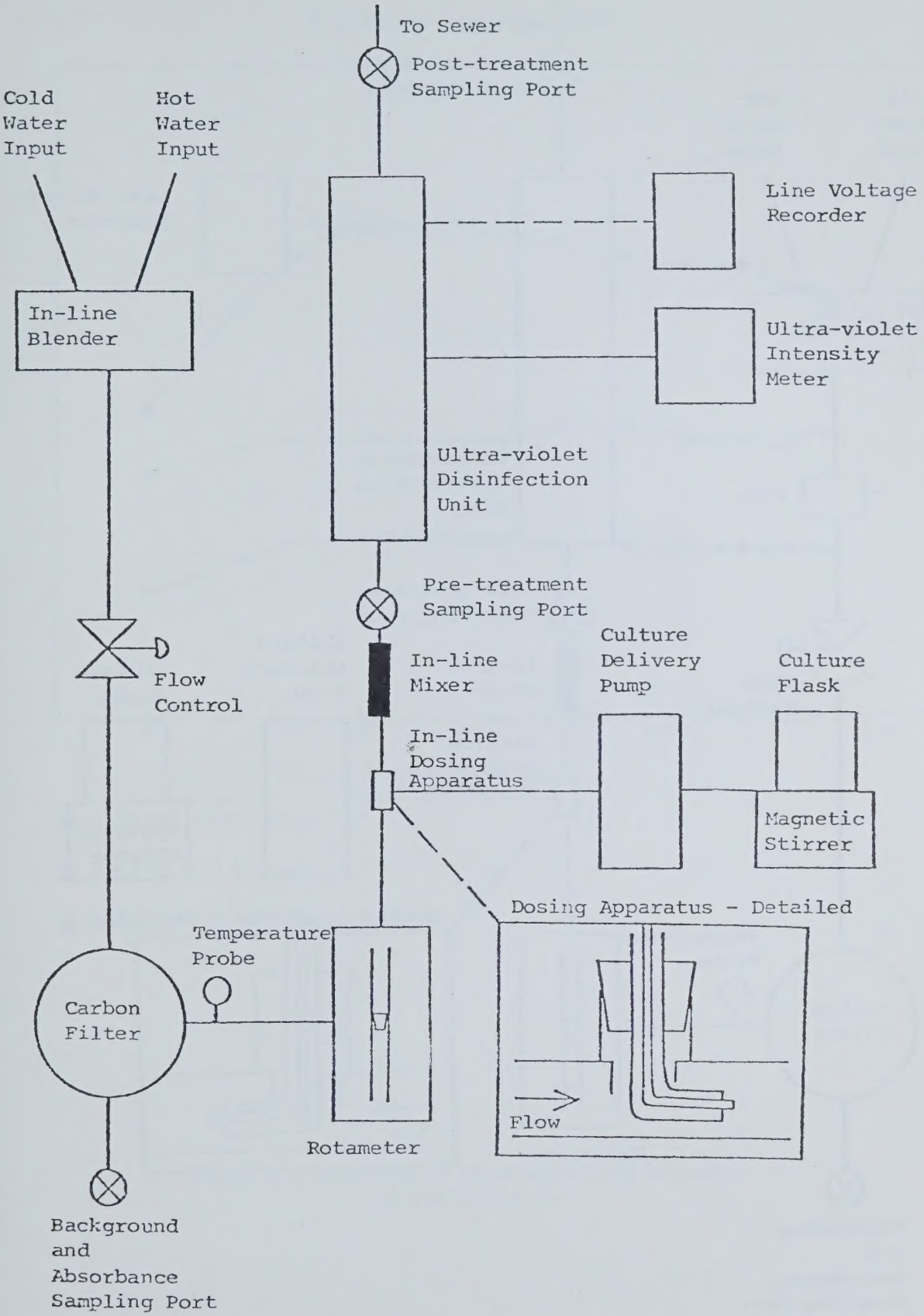

Figure 2. Schematic Drawing of Testing System

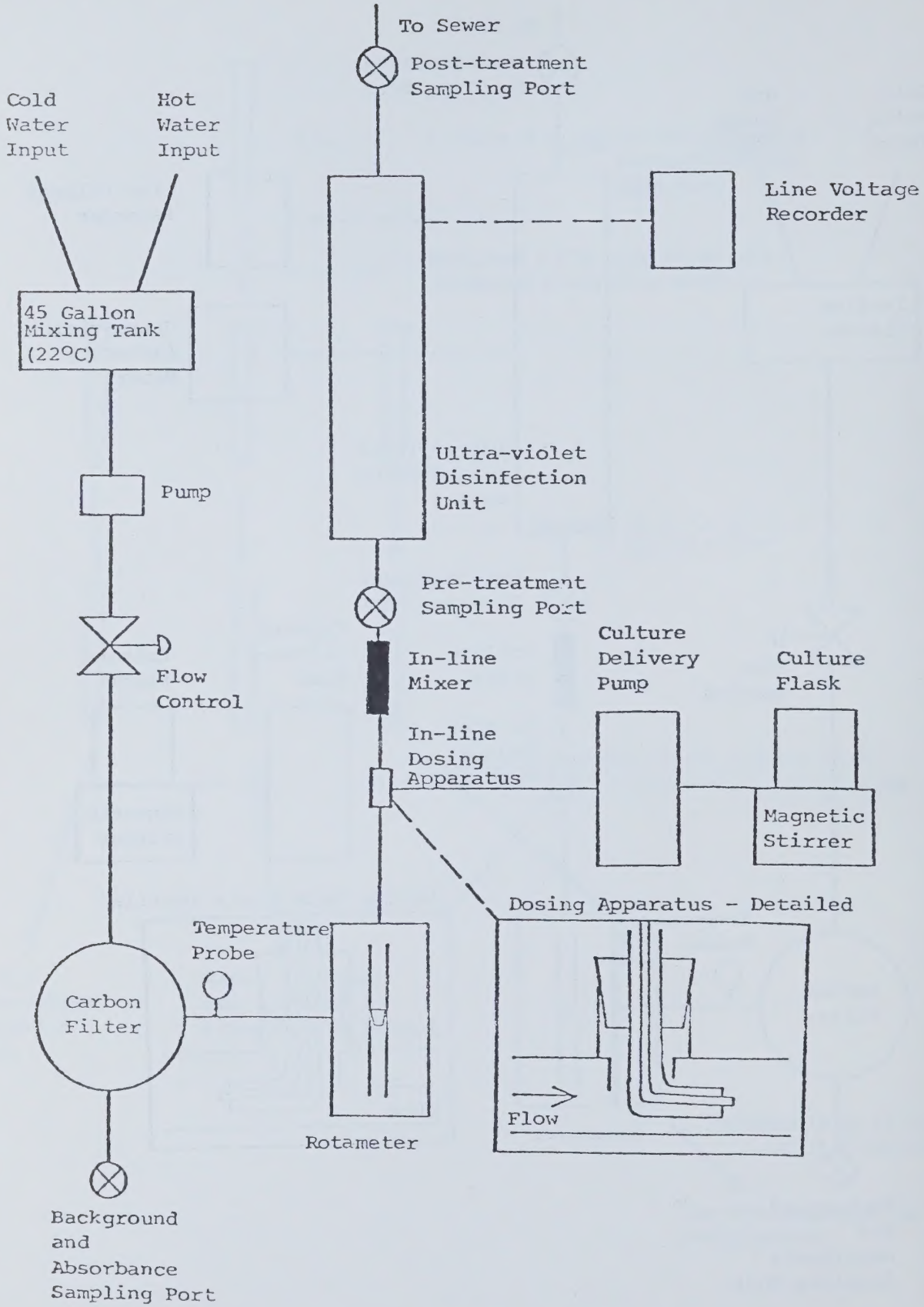

Figure 3. Schematic Drawing of Testing System
Low Flow Warm Temperature UNIT C

Conditions: High Flow, 22°C

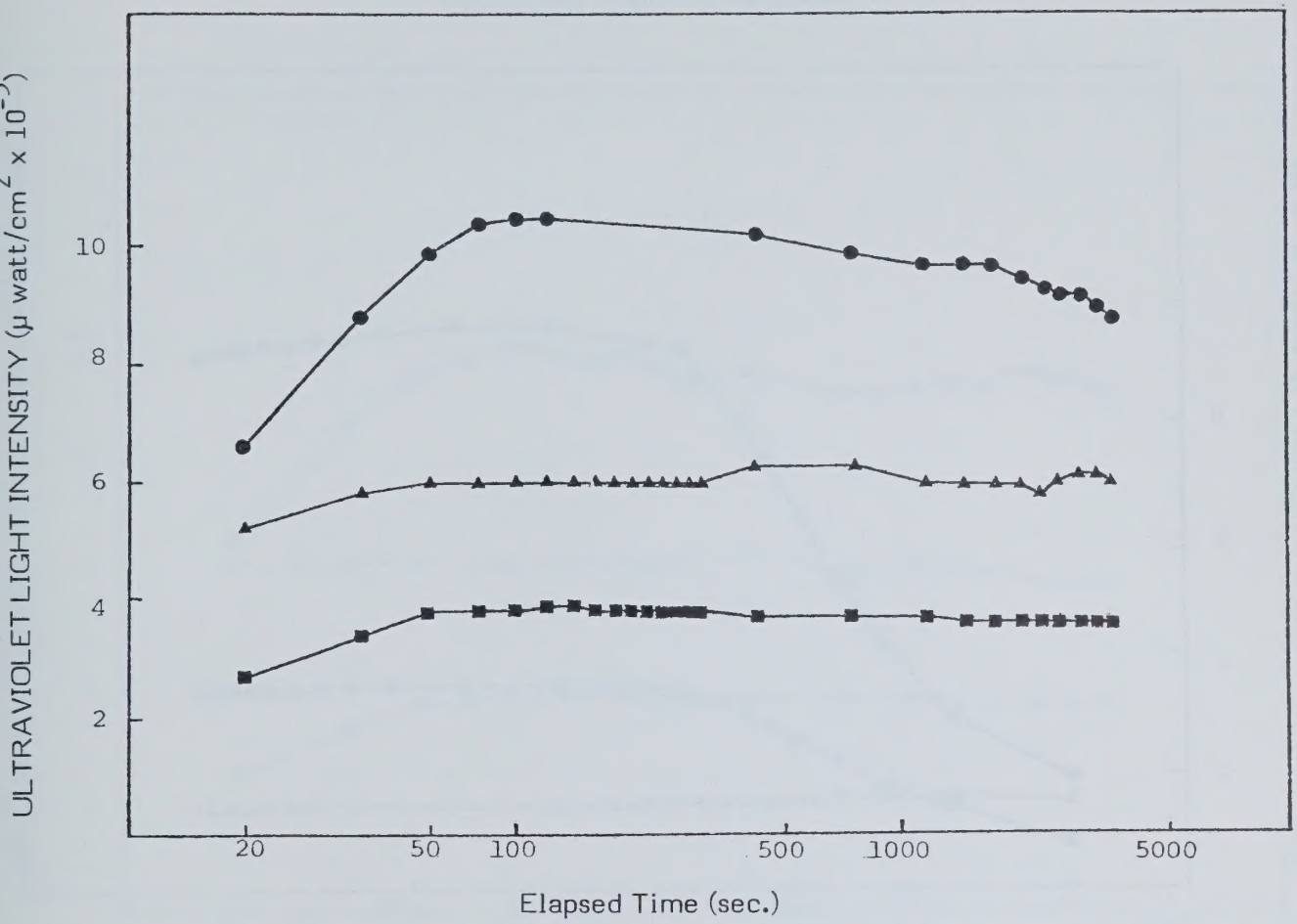

Figure 4. Comparison of Ultraviolet Light Intensity of the Test Units

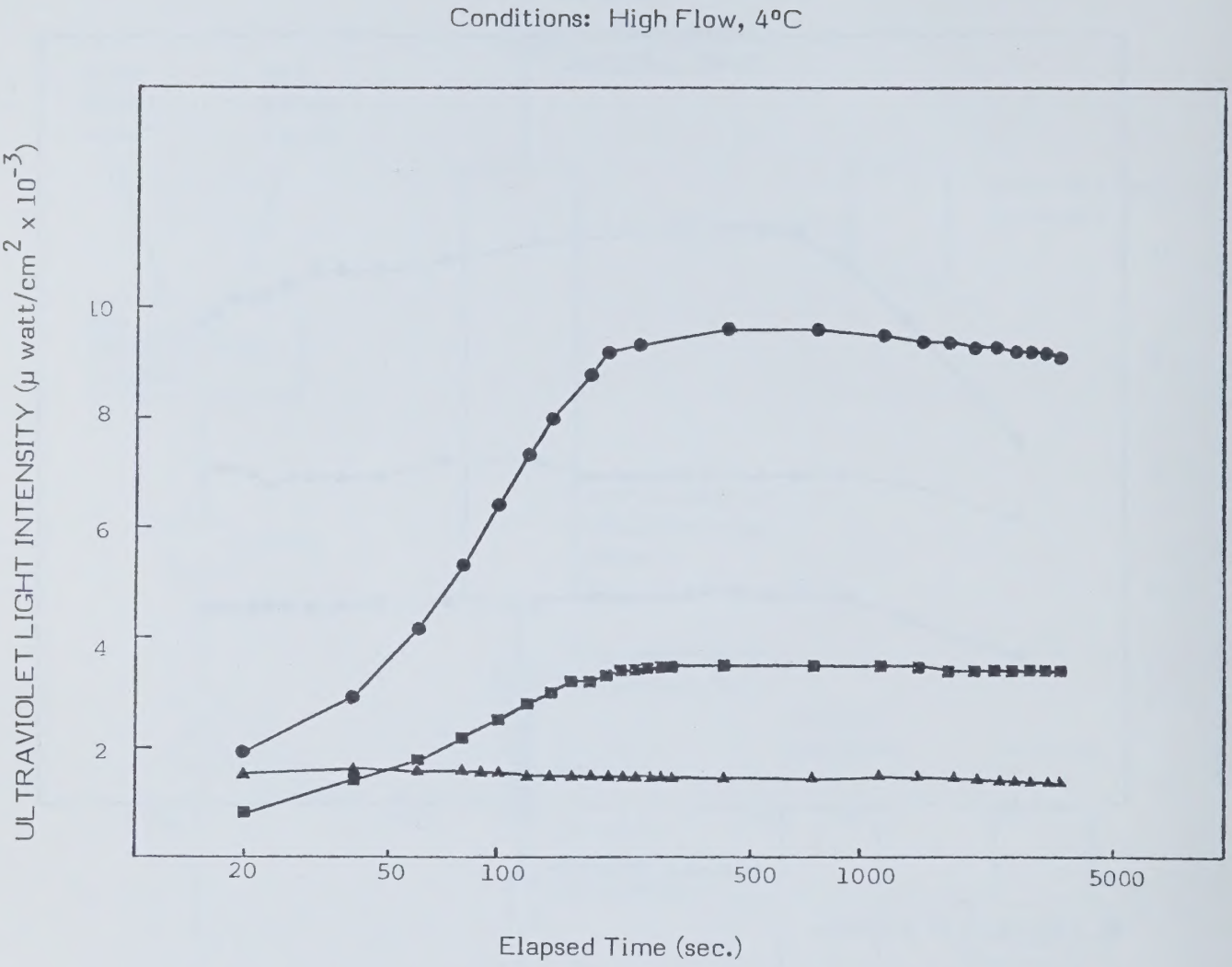

Figure 5. Comparison of Ultraviolet Light Intensity of the Test Units

Conditions: Design Flow, 22°C

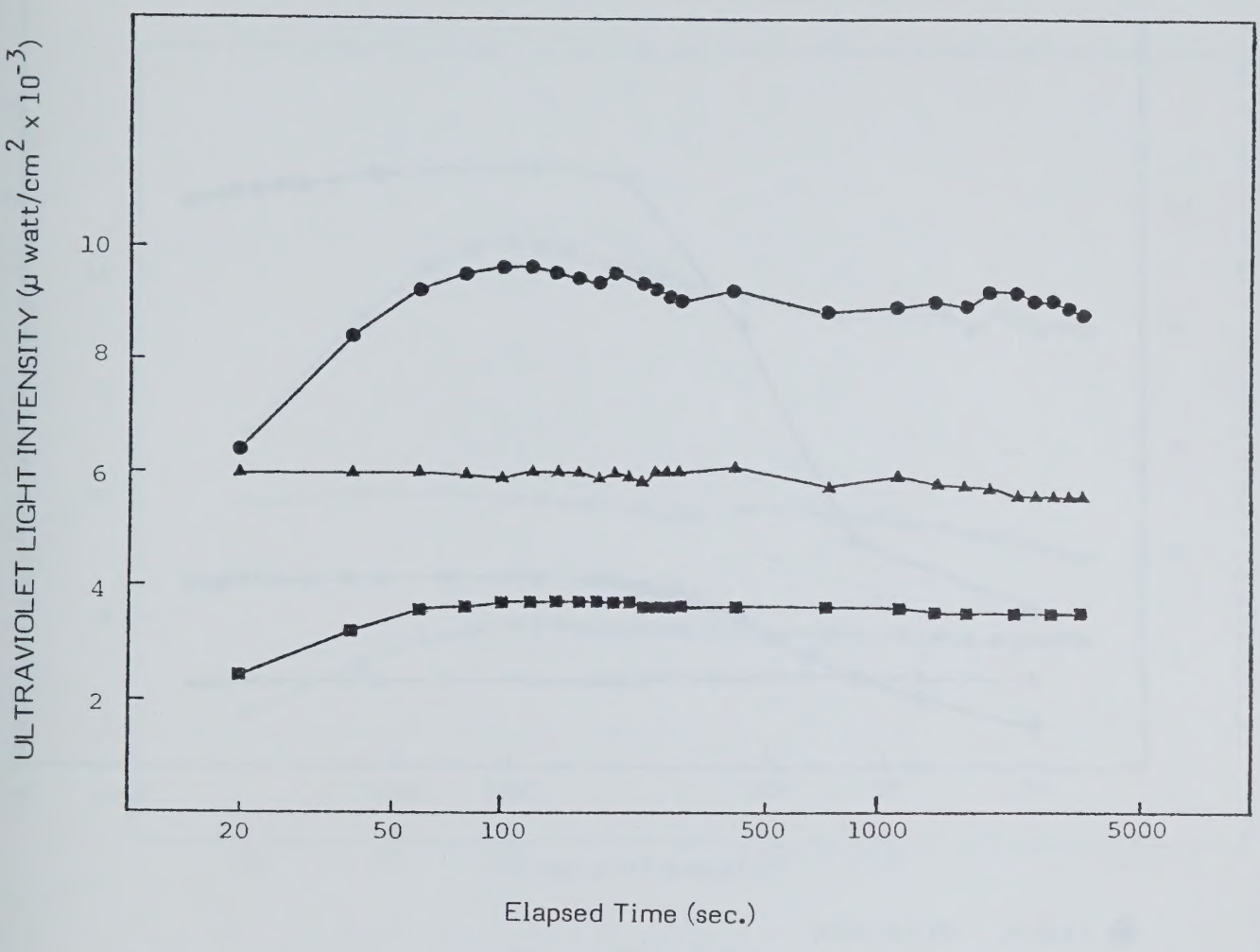

Figure 6. Comparison of Ultraviolet Light Intensity of the Test Units

Conditions: Design Flow, 4°C

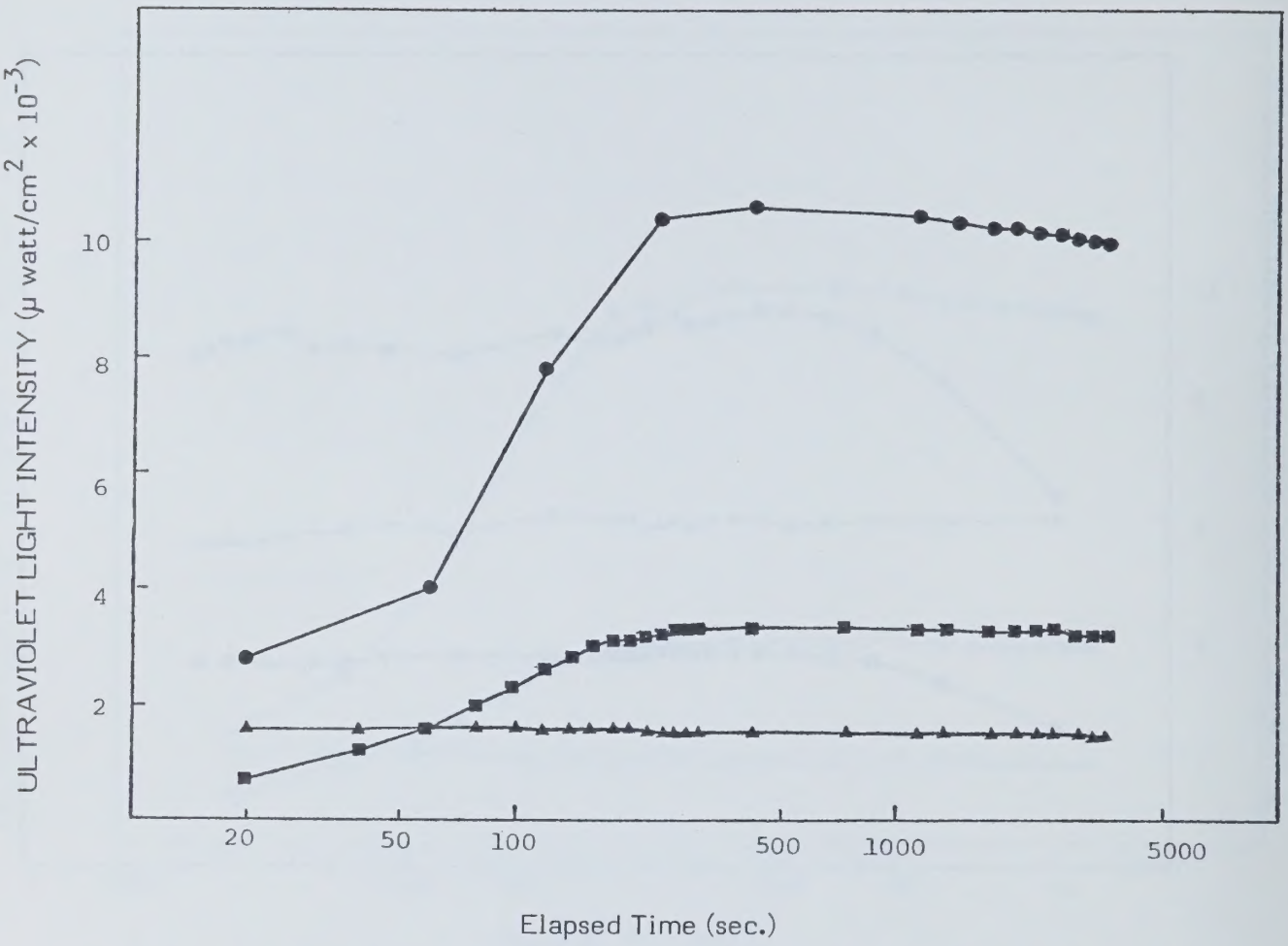

Figure 7. Comparison of Ultraviolet Light Intensity of the Test Units

Conditions: Design Flow, 22°C

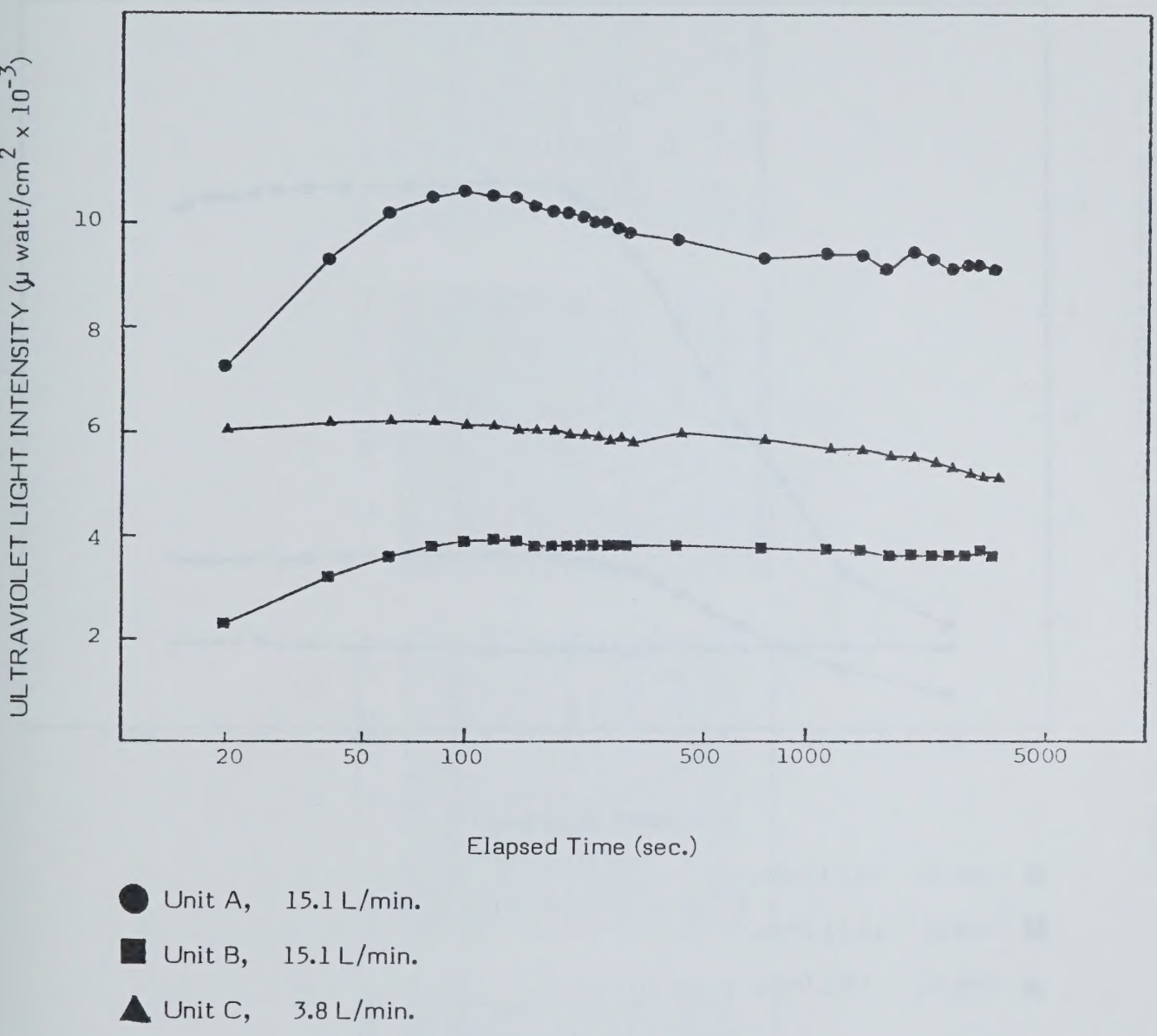

Figure 8. Comparison of Ultraviolet Light Intensity of the Test Units

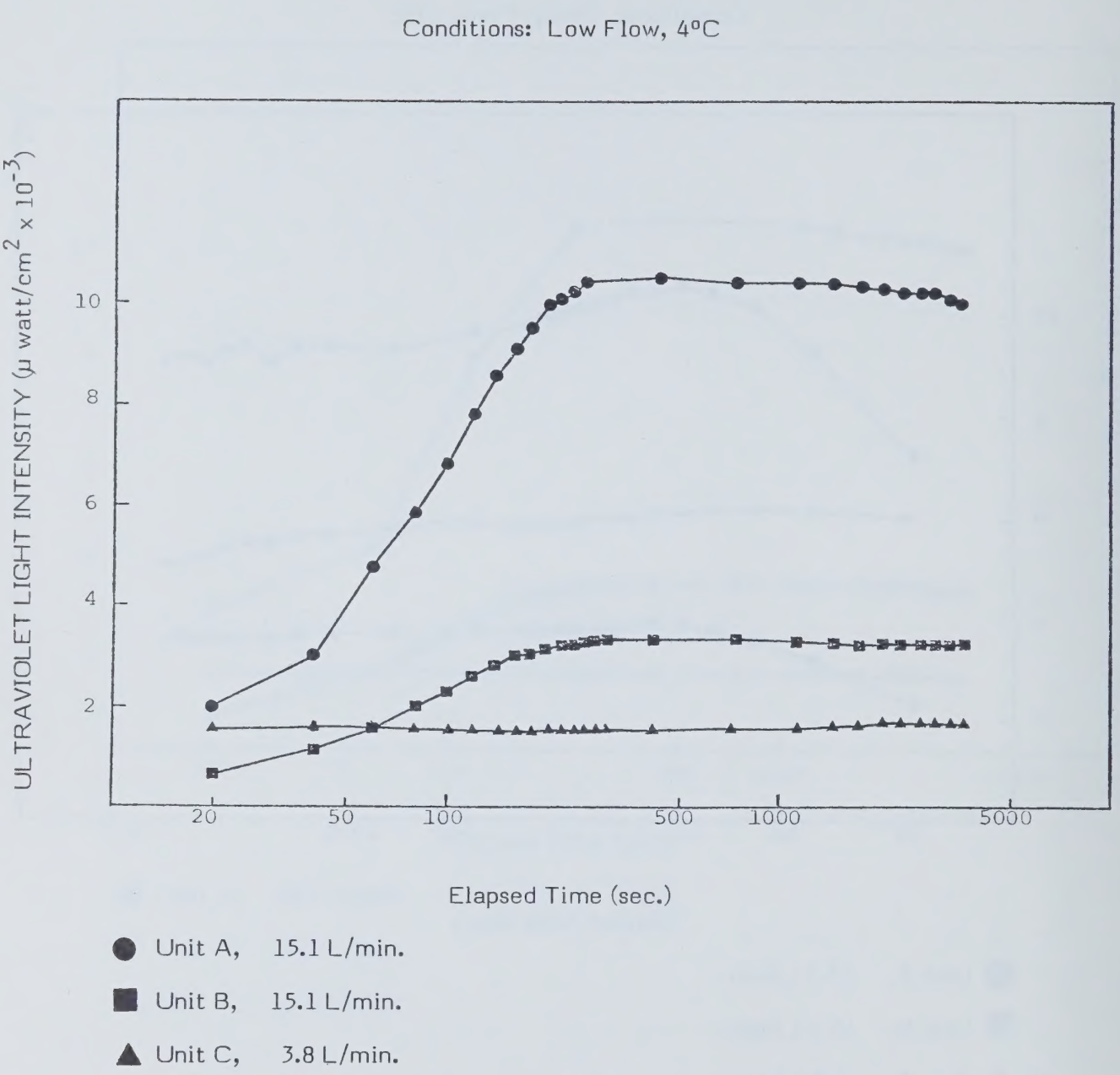

Figure 9. Comparison of Ultraviolet Light Intensity of the Test Units

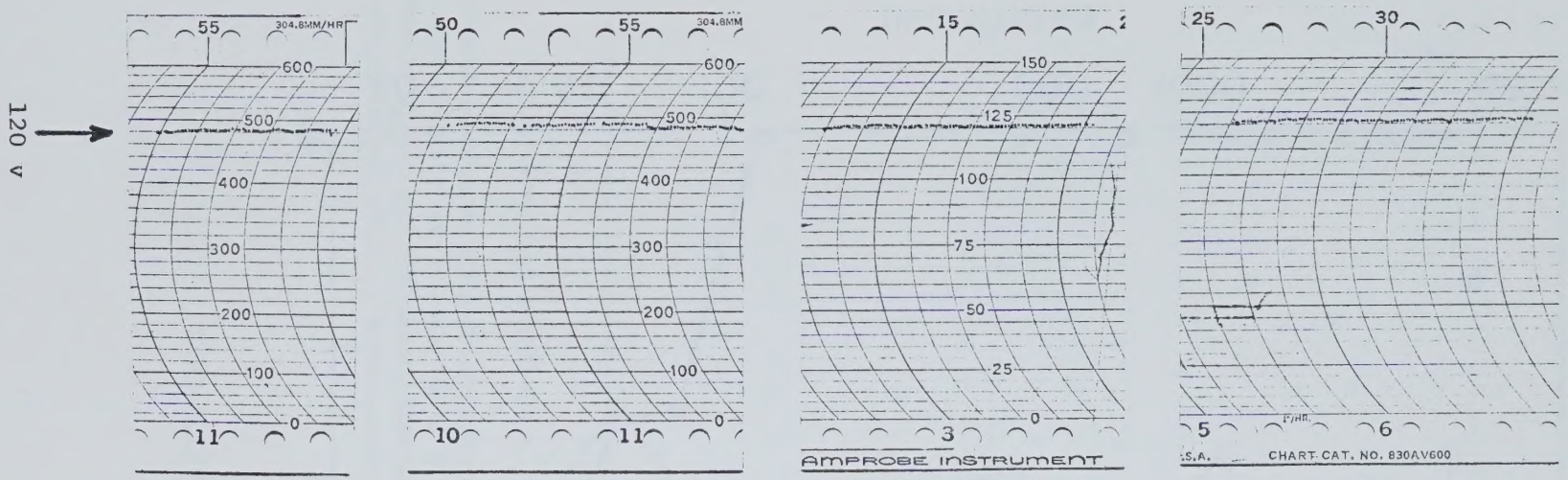

Figure 10. Typical Line Voltage During Test Run

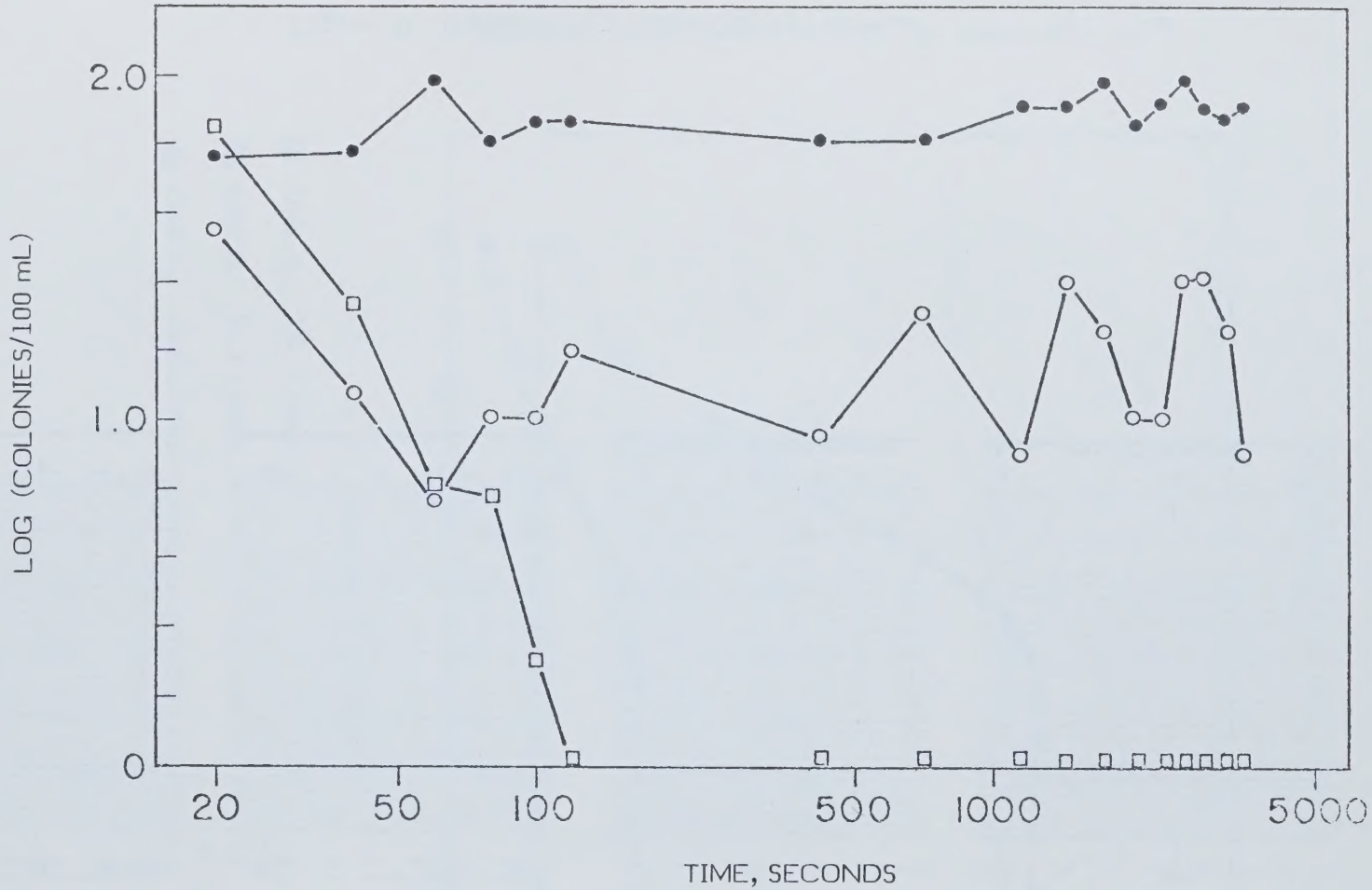

Figure 11. Bacterial recoveries from Unit C at three flow rates in 4.1°C water

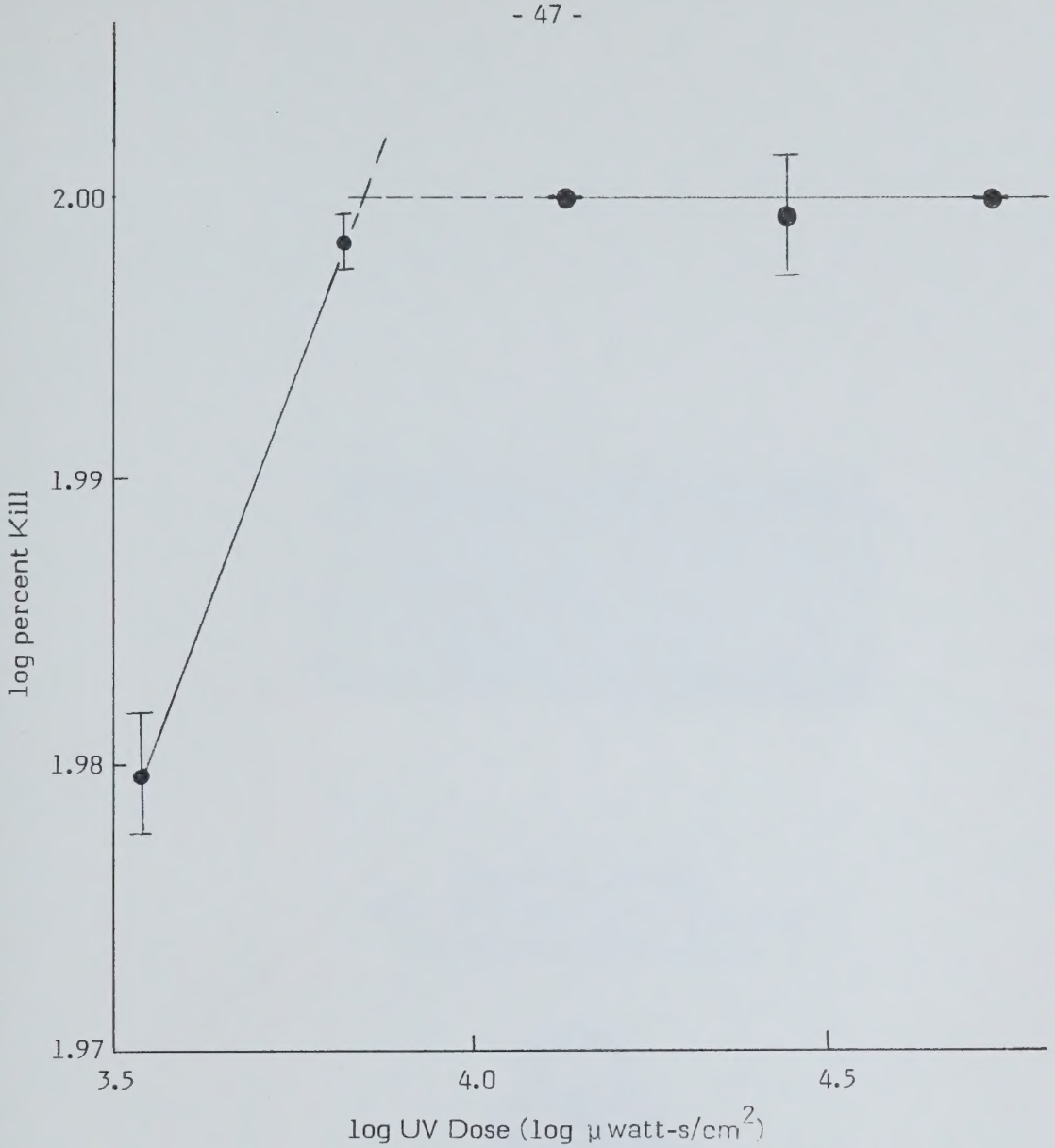

Figure 12. Relationship between percent bacterial kill and UV dose. Unit C, combined cold and warm water data. Points and bars represent arithmetic means plus or minus 1 standard deviation of 12 samples taken after a 2 minute warm-up.

CA1 HW 1179E33
Canada. DNHW. EHD.
79-EHD-33
LABORATORY TESTING OF POINT-OF-USE ULTRAVIOLE

RESOURCE CENTRE
INST. FOR ENVIRON'L. STUDIES
UNIVERSITY OF TORONTO